

Chapter 2

Established Thermomechanical Heat Engine Cycles

This chapter describes and discusses the four most common external combustion thermodynamic cycles: Stirling, Brayton, Ericsson, and Rankine. Internal combustion thermodynamic cycles, such as Otto, Diesel, and rocket, will not be considered, because it is impractical to use them for waste heat capture.

A thermodynamic cycle describes the processes of transferring heat into mechanical work, through the variation of temperature and pressure. This occurs in such a way as to complete a repeatable cycle, returning to the system's initial state. For each cycle, the theorized pressure–volume (PV) diagram will be presented, along with discussions of practical macro and micro electro mechanical systems (MEMS) engines.

There are an infinite number of possible thermodynamic cycles made up of several processes. The simplest cycles are defined by just three distinct thermodynamic processes (e.g. Lenoir cycle), while other conventional cycles may have five distinct thermodynamic processes (e.g. Miller cycle). Most cycles described in this chapter are defined by four distinct processes. The Rankine cycle is the exception; it can have a variable number of processes.

2.1 The Stirling Cycle

The Stirling cycle was first proposed by Robert Stirling in the early 1800s, although has had limited application until the middle of the twentieth century. Starting in the 1950s, companies such as Ford, General Motors, Kockums and Phillips [1] developed power applications at the kilowatt scale. These have included cars [1] and submarines [2, 3]). Although the Stirling cycle matches the Carnot cycle in terms of efficiency [4], it has a number of key disadvantages inherent in a practical engine design.

Interest in the Stirling cycle at large scale has recently increased. This is, due to its attractive theoretical efficiencies, its ability to use waste heat and renewable resources such as solar concentrators, and a wide range of fuels, since Stirling

engines are externally heated. In addition, the Stirling engine is one of the few heat cycles that can be optimized for almost any temperature range.

The use of nuclear energy as a heat source in a Stirling cycle was invented by Cooke-Yarborough from the Harwell Atomic Energy Laboratories (United Kingdom) [5] in 1967. This was a very simple device, based around free-piston Stirling engines. The engine did enter production; the HoMach TMG 120 was a 300-mm-diameter device that generated 150 W at about 10 % thermal-to-electrical efficiency. The device had a total mass of less than 100 kg.

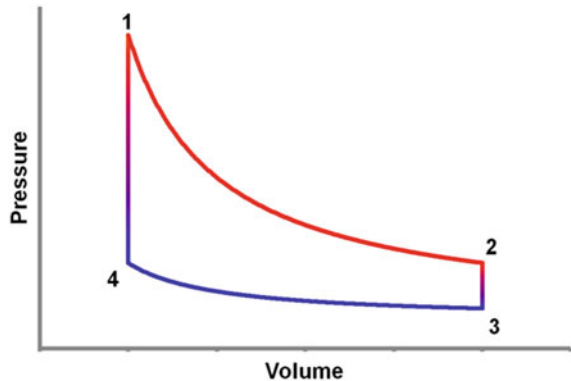
2.1.1 Theoretical Stirling Cycle

The theoretical PV Stirling cycle, shown in Fig. 2.1, is a heat cycle characterized by two isothermal reversible processes (1–2 and 3–4) and two constant-volume reversible processes (2–3 and 4–1). The first isothermal process (1–2) occurs at the high temperature side, where the working fluid is allowed to expand at constant temperature. The second part of the cycle is a constant volume process (2–3), in which the working fluid is cooled to the cycle's low-temperature point. Stage 3–4 is the low-temperature isothermal compression, in which heat is rejected from the cold side of the ideal engine. Finally, a second constant-volume process (4–1) occurs, in which heat is added to drive the working fluid back to the high temperature state.

2.1.2 Practical Macro Stirling Engines

In reality, the thermodynamic cycle shown in Fig. 2.1 can never be exactly reproduced. Instead, a practical Stirling engine will approximate this cycle. There are three common configurations that do this; these are referred to as the Alpha, Beta and Gamma Stirling engines, illustrated in Fig. 2.2.

Fig. 2.1 Pressure–volume diagram for the Stirling cycle



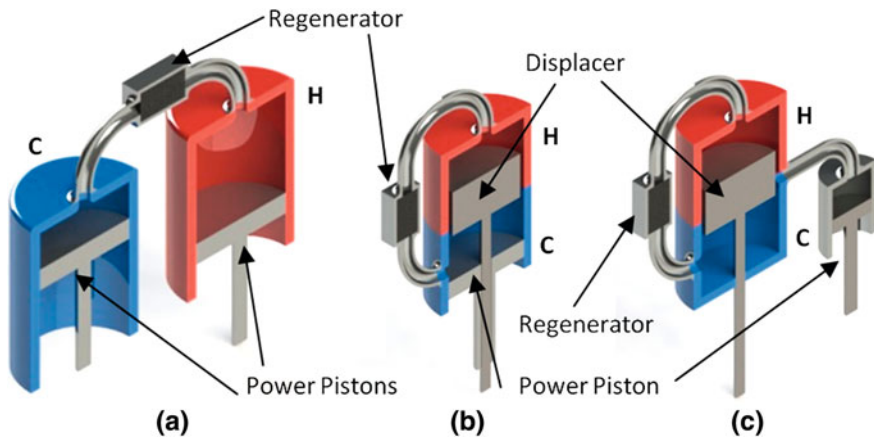


Fig. 2.2 Common topologies of Stirling engines; **a** Alpha, **b** Beta, and **c** Gamma. To follow the Stirling cycle, the pistons and displacer must be 90° out of phase

The Alpha cycle, shown in Fig. 2.2a, contains two working pistons; one for the hot side of the engine and one for the cold side. The cooling part of the cycle, in which the working volume is decreasing, causes the pistons to be drawn in. Thus, both the hot and cold side pistons need gas-tight seals. The tight seal drives up the friction losses, and necessitates higher working temperatures to achieve efficient engines.

The Beta and Gamma cycles, shown in Fig. 2.2b, c, consist of a single working piston with gas-tight seals, and a loose-fitting secondary piston (the displacer), which shuttles the working fluid between the hot and cold side. In the Beta type engine, the displacer and power piston are co-located in the same cylinder, while for the Gamma variant, the two pistons are each in their own cylinder. The reduced need for a gas-tight seal around the displacer means the losses are lower in both these types, although the Beta variant requires an additional seal where the connecting rod for the displacer passes through the power piston.

The Gamma variant has the lowest working friction. Combined with the ability to widely vary the relationship between displacer diameter and power piston diameter, this means it can be designed to be powered from very small thermal differences. A small thermal difference generates a small volumetric expansion, thus requiring a small displacement power piston relative to the swept volume of the displacer. Macro-scale designs for this style of Stirling engine can rotate from the thermal difference between ambient temperature and a cup of warm liquid, or heat emanating from human skin. At these low temperature differences, the efficiency of the system is necessarily low.

To improve efficiency, heat energy may also be stored in and rejected by a regenerator. The regenerator allows heating or cooling of the portion of the working fluid that never reaches the hot or cold side heat exchangers. Further, the regenerator allows a temperature increase or decrease of the working fluid without a change in volume (4–1 and 2–3 in Fig. 2.1). The effect of this is to maximize the

area of the temperature-limited PV diagram by filling out the corners, bringing the actual cycle closer to the ideal cycle.

Methods to improve performance include pressurizing the working fluid, and using low-specific-heat gases such as hydrogen and helium. Pressurizing the fluid increases the number of molecules in the working fluid, and low-specific-heat gases require less energy for a required temperature; pressure therefore rises. These methods require good seals where the cylinder is penetrated by pistons or piston rods.

A key advantage of the Stirling cycle is that it requires less complex mechanisms than other cycles; the designs can eliminate valves, which can impede fluid flow and increase mechanical complexity in other heat engines. Generally, the Stirling engine is quieter and more efficient at lower temperature differences and lower compression ratios. This drives a lighter design, due to the lower stresses involved.

2.1.3 MEMS Stirling Engines

Proposed MEMS implementations of Stirling refrigerators have been published, although no commercially available MEMS refrigerators are available to date. This section will outline the function of the Stirling cycle at the macro scale, and discuss some of the scientific challenges when applying this at the MEMS scale.

Due to the mechanical linkages required for the noted macro Stirling engines, they are unlikely to be useful at the MEMS scale. At the smaller scale, everyday items such as bearings, seals, and valves, can be problematic to manufacture. As such, any design that minimizes these items is likely to be easier to realize. Key to this are a variety of designs called free-piston Stirling engines. In these designs, the working fluid is completely encapsulated in a sealed volume, and power output is typically via magnets in coils or linear transducers. Cycle timing is provided by the movement of the working fluid between the hot end and the cold end, and by inertial mass and system resonance.

Published work on MEMS Stirling engines is limited, with most MEMS-scale Stirling work focused in the field of low-temperature cooling [6, 7]. This uses power input into the Stirling cycle to produce a temperature difference, rather than using a temperature difference to generate energy. Although the Stirling cycle is reversible, design optimization for refrigeration or energy generation, means that either design will probably not perform well when run in reverse.

Nakajima et al. [8] and Formosa et al. [9] both discuss miniaturization effects on efficiency and performance of Stirling engines. Nakajima et al. completes a dimensional analysis showing that as the surface area-to-volume ratio becomes larger with miniaturization, heat transfer through walls becomes more effective. Simultaneously, the ability to insulate the hot side from the cold side becomes more difficult, because they are closer together. Slide mechanisms and flywheels become problematic as friction forces begin to dominate. Formosa et al. found similar results, concluding that although specific power rises as size decreases, issues arise around sealing and friction at the piston/cylinder contact line. When a

membrane was used instead of a piston, thermal insulation between the hot and cold side fell dramatically.

At the moderate temperature range above 80 °C, Nakajima et al. [8] manufactured an engine with a swept power piston volume of 0.05 cm³, that provided output of 10 mW at 100 °C (hot) to 0 °C (cold). The power-to-weight ratio for the design was about 1 % of a full-scale design, at about 1 W/kg [8]. However, the authors suggest that this could be increased by 1–2 orders of magnitude by increasing the working fluid temperature and the hot side temperature. Efficiency may also be increased by selecting a different working fluid and increasing the working fluid pressures.

At moderate to high temperatures, a patent by Landis/NASA [6] explores the use of waste heat on board spacecraft (via radioisotope decay as the heat source) for generation of power. Although not explicitly noted, the patent indicates the intention to manufacture ‘hundreds or even many thousands of individual heat engines on a single six-inch round silicon wafer’. No performance results are available, and no indication of whether the device has been realized could be found.

2.2 The Brayton Cycle

The Brayton cycle was first proposed by George Brayton in the mid 1800s. Early implementations of the cycle used pistons as the compressor and expander. The ‘modern’ Brayton engine has a very different configuration. It involves rotating compressor and expander fans, instead of the pistons used by George Brayton, although they follow the same cycle. These turbine engines have found large-scale use for jet propulsion, gas turbine generators and solar thermal generators. The cycle can function as an internal or external combustion engine. Its ability to function as an external combustion engine makes it of interest within this study.

2.2.1 Theoretical Brayton Cycle

By ignoring any irreversibility, the Brayton cycle can be characterized by two isentropic processes (1–2 and 3–4) and two isobaric processes (2–3 and 4–1), as shown in pressure volume (PV) and temperature–entropy (TS) diagrams in Fig. 2.3. The area enclosed by the curves indicates the work produced by the cycle.

By increasing the pressure ratio across the compressor ($P_r = P_1/P_2$) from 2 to 2', as shown in Fig. 2.3, it is possible to increase the net work output and achieve a greater efficiency. This increase is indicated by the increased area formed by the dashed line cycle, 1–2'–3'–4. A similar cycle to the Brayton is the Ericsson cycle. The key difference is that the two isentropic processes in Fig. 2.3 are replaced with two isothermal processes. The practical effect of this is to move Point 2 horizontally to the left and Point 4 horizontally to the right on the PV diagram.

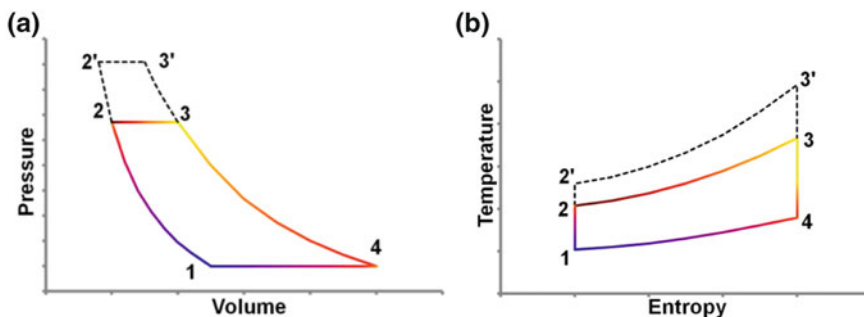


Fig. 2.3 a Pressure–volume and b temperature–entropy diagrams for the Brayton cycle

2.2.2 Practical Macro Brayton Engines

A practical Brayton engine following the Brayton cycle will differ from the idealized cycle shown in Fig. 2.3. This is due to irreversible effects such as stray heat transfer, friction losses, and pressure drops in the working fluid caused by fluid movement. These effects increase the work consumed by the compressor and reduce the work performed by the expander. This reduces the engine's efficiency compared with the idealized cycle.

A Brayton engine can operate as an open cycle or a closed cycle. Figure 2.4 shows both operations. Each aims to practically reproduce the theoretical cycle using a compressor, heater (heat exchanger or combustor), and expander.

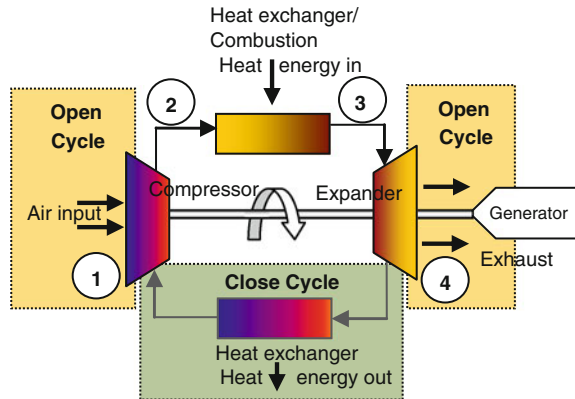
In the piston or turbine configuration, the engine operates by drawing air into the compressor, in which pressure and temperature rise (1–2). The high-pressure air travels into the heater, where fuel is burned or external heat is added, which increases pressure and temperature at a constant volume (2–3). The resulting high-temperature gas then enters the expander, where it expands, performing work (3–4). In the open-cycle engine, the gas is rejected to the atmosphere. In the closed-cycle engine, the gas travels to a heat exchanger, where it is further cooled, and then fed back into the compressor (4–1).

Not shown in Fig. 2.4 is the regenerator, often used in a Brayton engine to preheat the working fluid entering the heater [10]. Less heat is then needed to bring the working fluid up to maximum working temperature. This maximizes the work produced by the heat available, increasing the efficiency of the engine.

For the closed-cycle engine, a heat exchanger is required between the expander and compressor, by reducing the fluid inlet temperature the temperature difference between the hot and cold sides of the engine is maximized, thus maximizing the Carnot limit.

It is also possible to increase the work output of a Brayton turbine when operating between two pressure levels, by expanding the gas in stages and reheating it in between. This results in a more complex PV diagram [11], with an

Fig. 2.4 Schematic of the Brayton cycle turbine or piston engine



increased volume enclosed by the cycle, and hence more work is performed without increasing the maximum temperature of the cycle.

The Brayton cycle commonly uses turbines for the expander and the compressor. However, it can also use positive displacement mechanisms, such as pistons, as described by Rosa [12]. This is a closed-cycle engine that contains the same components shown in Fig. 2.4, with pistons used for the compressor and expander.

Commonly, Brayton closed-cycle engines use helium as the working fluid, because it has both high thermal conductivity and low specific heat compared with air. This increases the efficiency of the engine. The efficiency of the closed-cycle engine can be improved over a wide range of power demands by adjusting the gas pressure and heat input [13].

2.2.3 MEMS Brayton Engines

At the MEMS scale, no external heat Brayton engine has yet been developed. However, Massachusetts Institute of Technology has directed significant research into applying an internal combustion Brayton cycle turbine [14, 15]. The schematic of this engine is shown in Fig. 2.5. The authors outline many of the design challenges that would apply to both an internal and external combustion MEMS engine. These include the increased viscous forces in the fluid, reduced strength of materials, and increased surface area-to-volume ratios. The designed device consists of a series of layers, etched from silicon using photolithography [15], and stacked to form the complete engine. The device, shown in Fig. 2.6, is 20 mm in diameter and 3 mm thick, and is designed to produce approximately 10 W of output power [15]. Epstein et al. [15] claims that the power density of these devices approaches that of a full-sized Brayton turbine, although efficiency of the device still remains low.

Fig. 2.5 Schematic of H₂ demo gas turbine chip. Image sourced Epstein [14], reprinted with permission from ASME. Copyright 2003, ASME

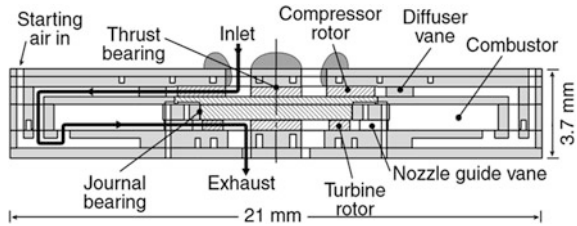
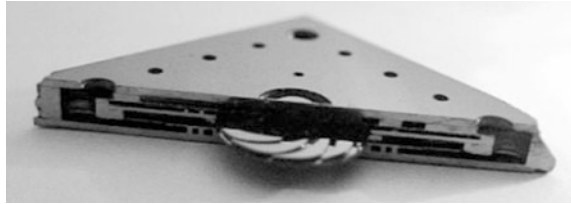


Fig. 2.6 Cutaway of the experimental H₂ demo gas turbine chip. Image sourced Epstein [14], reprinted with permission from ASME. Copyright 2003, ASME



2.3 Rankine Cycle and Other Vapor Cycles

The most common vapor cycle is the Rankine cycle, named after William John Macquorn Rankine (1820–1872). He contributed greatly to the theory of thermodynamics and thermodynamic processes, and was the first to fully describe the thermodynamic process of this cycle. Most heat engines built in the eighteenth, nineteenth and early twentieth centuries (i.e. steam engines) operate using this thermodynamic cycle, and they kick-started the industrial revolution. The Rankine cycle is the thermodynamic operational cycle of heat engines commonly used to drive electrical generators, such as the steam-based cycles used in coal-fired, nuclear, and some gas-fired power stations. Today, steam turbines produce most of the world's electrical energy, including 90 % of electrical energy in the United States [16]. Other novel vapor cycles exist, and will be discussed below.

2.3.1 Theoretical Rankine Cycle

The Rankine cycle heat engine uses a two-phase working fluid (liquid and gas) and is usually a closed cycle. Within one working cycle of the engine, the working fluid passes through both the gas and liquid phases, via the input, and then extraction, of heat. At the cold side of the cycle, the working fluid phase is liquid, and at the hottest point in the cycle, it is a vapor or gas. At various other periods within the cycle, the working fluid is a combination of liquid and gas: i.e. a vapor.

Figure 2.7 shows a PV and TS diagram of a Rankine heat cycle, and Fig. 2.8 shows a schematic of an ideal Rankine cycle engine. The cycle typifies modern steam turbine generators, in which the liquid working fluid is pressurized and

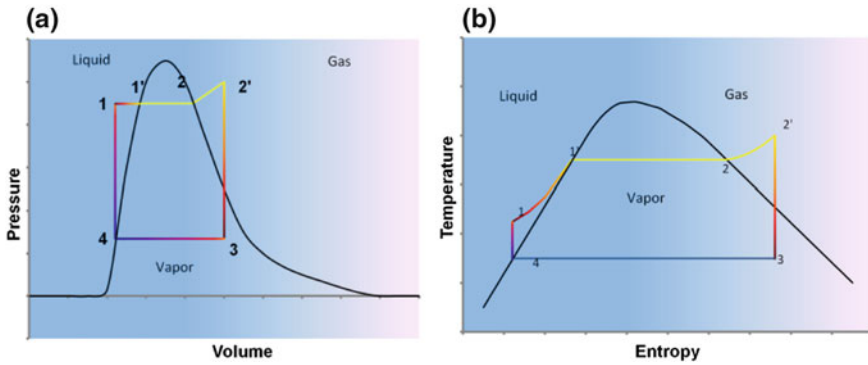


Fig. 2.7 **a** Pressure–volume and **b** temperature–entropy diagrams for the Rankine cycle. Points 1–4 are replicated on the schematic (Fig. 2.8). The shaded background indicates transformation from a liquid to a gas

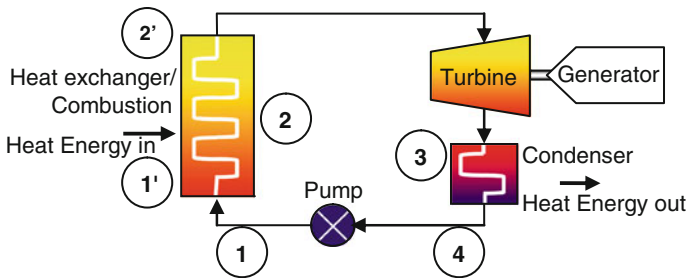


Fig. 2.8 Rankine cycle schematic

moved (by a pump, 4–1) to a heater, where it is vaporized (evaporator, 1–2) to either a high-pressure vapor (2) or a gas (2'). The vapor or gas then cools and reduces in pressure through an expander (turbine or piston, 2/2'–3) to produce useful mechanical output: e.g. to drive an electrical generator. The exhausted vapor is cooled to 100 % liquid via a reservoir or cold side heat exchanger (3–4), and then cycled back through the pump.

2.3.2 Practical Macro Rankine Engines

A common historical arrangement is that of the positive displacement, reciprocating piston engine. This engine was used to extract work from steam, as used in most steam locomotives and stationary steam engines of the eighteenth, nineteenth and early twentieth centuries. Conceptually, other arrangements of positive displacement expanders are also possible (e.g. Wankel rotor [17], scroll rotor [18], gerotor [18]).

The maximum working temperatures of macro-scale Rankine engines are limited by the materials used in their construction. The maximum working temperature is usually about 550 °C—above this, stainless steel ‘creeps’ (deforms permanently under a constant but relatively low stress). The minimum hot temperature, or the maximum cold temperature, at which a Rankine cycle can operate is a function of the pressure and temperature at which the working fluid changes phase.

The power density of a Rankine cycle engine, in the case of a steam engine, is in the order of 100 W/kg. The expected power level for MEMS-scale Rankine technology is about 12 kW/kg [19], with efficiencies in the range of 1–11 % [20].

Macro-scale Rankine cycle engines have achieved 47 % overall efficiency [21]. The efficiency of a modern, coal-fired, steam turbine power generator is 39 % or more [22]. For a hot operating temperature of 565 °C, and cold side temperature of 30 °C, this equates to a theoretical Carnot limit of 64 %, and therefore an overall efficiency of about 61 % of the Carnot limit at these temperatures.

A primary advantage of vapor cycles, and by inference Rankine engines, is the highly efficient pumping afforded by the use of a liquid phase at cold side temperatures. Most other heat engines that rely on a working fluid use gas only. As a result, they suffer from greater pumping losses, which may be magnified as engine speeds rise. A further advantage afforded by the Rankine cycle is the simplicity with which regeneration can be achieved. Regeneration is the transfer of heat from the working fluid after passing through an expander (e.g. turbine, piston, rotor) to the working fluid before it enters the evaporator (3–1). These advantages, combined, allow a high overall thermal efficiency.

A potential disadvantage of vapor cycles is that the properties of the working fluid must be well matched to operating temperatures and conditions. This limits the range of temperatures at which an engine operates, because the working fluid must be liquid at cold side temperatures and pressures, and reach unsaturated vapor at the hot side temperature. An unpredictable, uncontrollable, or low-grade heat energy input may render a vapor cycle engine ineffective. A well-tuned engine with controllable, predictable heat input circumvents this disadvantage. A further disadvantage of many Rankine engines—and in particular, steam turbines—is that during the expansion phase, not all of the heat energy can be extracted from the vapor. This is due to condensation of the working fluid, which contributes to blade erosion. As a result, some heat is lost through the condenser, rather than doing useful work.

2.3.3 MEMS Vapor Cycle Engines

The past two centuries have seen many publications relating to investigation and research of Rankine cycle heat engines. At the MEMS scale, Frechette and Lee have designed, built, and characterized a micro-fabricated steam turbine heat engine [19, 23]. The original concept was shown in a sketch in [19] and below in

Fig. 2.9. A recreation of the manufactured engine, including the turbine, as characterized in [23], is shown below in Fig. 2.9.

The engine uses one rotating assembly, shown in Fig. 2.10, which includes both the expansion turbine and the fluid compressing pump. The condenser is located on the lower, cold side of the device, and the evaporator on the upper, hot side. The rotor is supported by a fluid bearing, and uses the working fluid to support the mechanical loads.

The work performed by this group since 2000 includes the design and development of the system [19, 24], optimizing the bearings to support the rotating components [25], developing the rotating subsystem (including the expander turbine and the fluid pump) [23], fabricating and characterizing the device [24], and designing micro-channel heat sinks [26]. The primary advantage of this form of micro heat engine is reported as high specific power output (1–10 W per cm^2) [19], with the trade off being low overall efficiency (e.g. 7.2 %) [24]. This research group has spent more than a decade developing the device to its current state. It appears work is continuing; at the time of writing, the group's most recent articles were published during 2011 [24].

A group of researchers from Washington State University, with a number of collaborators, have developed a device they call the P³ micro heat engine [27]. The device uses a working fluid to deflect a membrane from which energy can be extracted. It relies on the phase change of the working fluid from liquid to gas to cause expansion, and is therefore an example of a vapor cycle heat engine. The researchers have claimed:

‘The prototype micro heat engine is an external combustion engine that converts thermal power to mechanical power through use of a novel thermodynamic

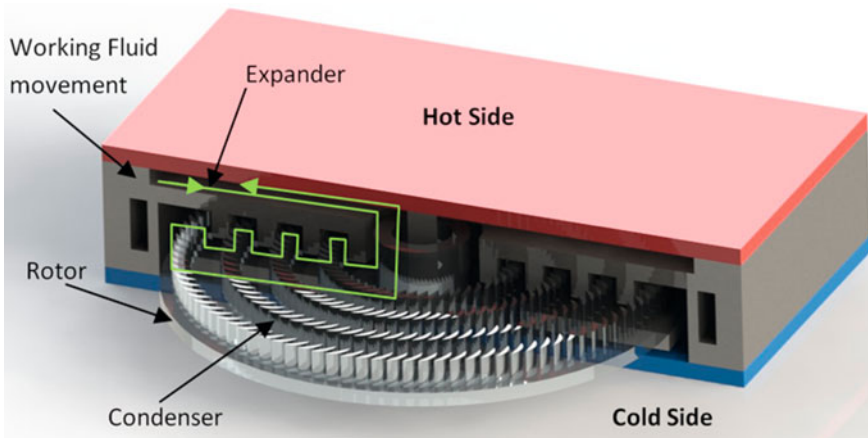


Fig. 2.9 Cross sectional schematic of experimental micro steam turbine engine [19]. The working fluid expands in the expander, does work on the turbine and condenses in the condenser. A pump on the rotor shifts the fluid back to the expander to allow for a repetitive cycle

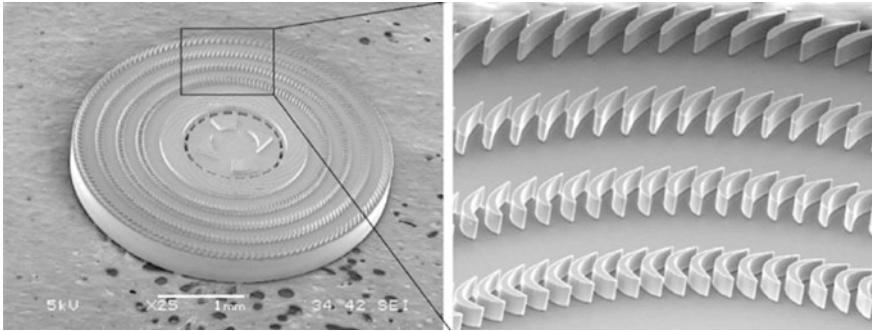


Fig. 2.10 Close-up of micro steam turbine rotor [24], note that reverse blades are located on the stator. © 2011 IEEE. Reprinted, with permission, from IEEE/ASME Journal of Microelectromechanical Systems [35]

cycle [...] the engine consists of a cavity filled with a saturated 2 phase working fluid, bounded on top and bottom by thin membranes' [27].

Figure 2.11 shows a cross-sectional sketch of the heat engine.

The engine works via expansion and contraction of the vapor bubble (0.6 mm^3), as heat is added through the heat input resistive coil and extracted via the lower thin membrane. This causes the upper and lower membranes to deflect, due to the pressure differential between the vapor bubble and the surrounding atmosphere. When the heat input is turned off the deflection of the membrane reduces. The lower membrane is comprised of a piezoelectric membrane, which creates electrical energy upon deflection and restoration. The piezoelectric membrane can also compress the volume of the vapor bubble before heat is added.

The researchers responsible for the development of this engine claim that a primary advantage of this methodology is that 'it opens the possibility of approaching the ideal Carnot vapor cycle efficiency'.

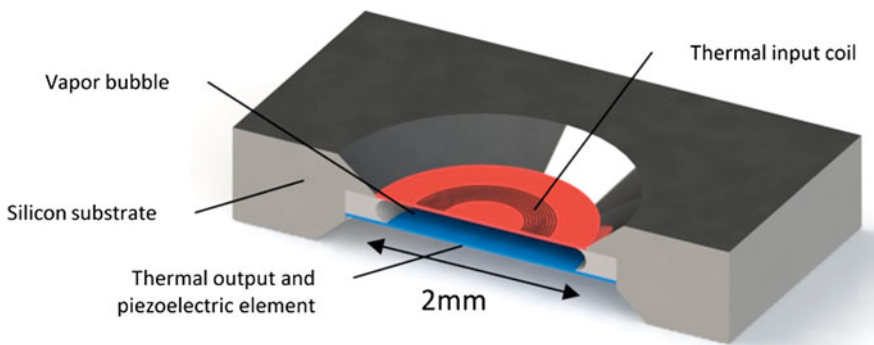


Fig. 2.11 Cross-sectional sketch of P³ micro heat engine [27]

The research group has performed further work to improve both the engine and associated heat source. This includes fabrication and characterization of a thermal switch [28], fabrication and addition of a micro-capillary heat exchanger inside the working chamber of the engine [29], further testing of the engine including micro-capillaries and switch [30], and the addition of a Swiss roll combustor to provide a heat source for the engine [20]. From the group's 2012 publication [31], the engine was reported as producing power at 'a second law efficiency of 16 %', i.e. 16 % of the Carnot limit.

2.4 The Ericsson Cycle

The Ericsson cycle is named after John Ericsson (1803–1889), who built and patented several different heat engines using various thermodynamic principals of operation. Of these engines, some operated using what is now known as the Ericsson cycle [32]. This cycle is rarely used by modern heat engines, although there are some notable examples from the nineteenth century.

The theoretical efficiency for the Ericsson cycle is equal to the Carnot efficiency for the same limiting hot and cold temperatures. However, practical engine designs cannot match the Carnot efficiency limit.

2.4.1 Theoretical Ericsson Cycle

Analysis of a theoretical engine using gas as the working fluid shows the Ericsson cycle consists of two isothermal and two isobaric processes.

A description of an ideal Ericsson cycle engine using a gas as the working medium, as shown on the PV plot in Fig. 2.12, follows. During isothermal compression (1–2), the working gas is compressed at constant temperature. Heat is added to the gas (2–3) at a constant pressure (isobaric), normally achieved by passing the working gas through a regenerator en route to a heated cylinder. Isothermal expansion (3–4) is normally achieved by a working piston/cylinder expanding while the incoming gas is at constant temperature (the gas is pre-heated by the regenerator, with final heat addition via a heater). Isobaric rejection of heat (4–1) is again normally achieved through use of a regenerator. The regenerator absorbs the heat from the exhaust gas. The heat is then used to increase the temperature of the incoming charge of gas (2–3).

Figure 2.13 shows a schematic of one of the many variants of the Ericsson cycle. The fluid is heated at a constant pressure through the regenerator (1–2 in Figs. 2.12 and 2.13). The fluid is then expanded isothermally through a turbine, held at constant temperature by the hot reservoir (2–3). It is during this stage of the

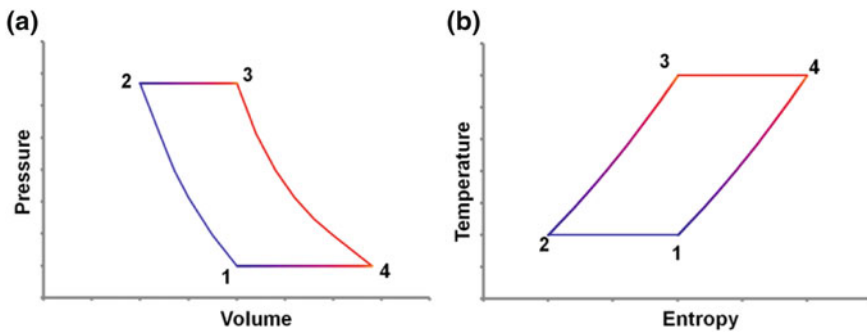


Fig. 2.12 **a** Pressure–volume and **b** temperature–entropy diagrams for the Ericsson cycle

cycle that energy is harvested. The working fluid is then cooled through a regenerator, at constant pressure. The heat given up at this stage (3–4) is used to heat the fluid between 1 and 2. The fluid is then compressed isothermally to its initial state through a compressor, which is held at a constant temperature by the cold reservoir. Energy input is required at this stage (4–1). This energy can be provided by direct mechanical connection to the turbine.

The two isothermal processes allow the Ericsson cycle to reach a theoretical efficiency equivalent to the Carnot limiting efficiency. As mentioned above, the regenerator allows this to occur in a practical engine, because the working gas temperature can be increased to the hot side temperature before the addition of heat from an external source. This allows the external heat to then be added at the constant hot side temperature. The corollary also holds true; the regenerator allows the exhaust gas to be cooled to the cold side temperature at constant pressure. In practice, the regenerator is simply a vessel with a large surface area and a high overall heat transfer coefficient, which allows the heat to be absorbed and rejected quickly to and from the working gas.

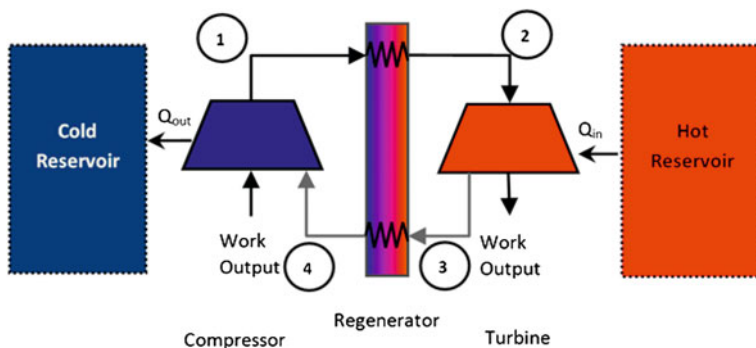


Fig. 2.13 Schematic of an ideal Ericsson cycle

2.4.2 *Practical Ericsson Engines*

Ericsson described the engines he produced, which operated using the basic principal of the Ericsson cycle, in patents such as [33, 34]. Although they generally followed the processes outlined in [Sect. 2.4.1](#), these were piston engines, predominantly using air as the working gas.

The engines described in [33] are similar in concept and are each comprised of two mechanically connected pistons; a series of valves; a regenerator; mechanical linkages, to ensure the valves and pistons operate in synchronicity; a flywheel, to store and impart energy throughout the cycle; a firebox, to apply heat; and passages, to allow movement of the working gas between various parts of the engine. The engines are designed to operate in either closed or open cycle, through use or deletion of a connection pipe from the exhaust of the working cylinder to the intake of the other.

A more common example of a practical Ericsson engine is through modification to Brayton cycle engines (e.g. turbines). In these, the use of intercooling, reheating and recuperation in stages can achieve an approximation of the Ericsson cycle (see [Sect. 2.2](#)).

A further example of an Ericsson cycle device is the Johnson Thermo-Electrochemical Converter System (JTEC). While this device does not use a working gas in the traditional sense, the inventor describes it as operating on an Ericsson cycle. This device is explained in more detail in [Sect. 5.5.1](#).

An obvious advantage of any engine that uses the Ericsson cycle is its high thermal efficiency. This is due to the two isothermal processes, during which heat is accepted and rejected at (near) constant temperature. Practically, this is not possible, but the process allows a much closer approximation of the ideal Carnot efficiency than most other engines: a notable exception being the Stirling cycle engine. Another advantage of an Ericsson engine is that it can be open cycle if using air as the working gas. This negates the need for heat sinking, because the intake air will always be at ambient temperature (maximizing the temperature difference, and therefore efficiency).

The Ericsson cycle is often compared to the Stirling cycle, due to the theoretical ability for either of them to reach the Carnot efficiency limit. However, an Ericsson gas engine is arguably more complicated than a Stirling engine of comparable performance. The traditional Ericsson engine's increased complexity is in the design and inclusion of the valves it requires to operate: in particular, the mechanical or other arrangement required to close and open the valves at the correct points in the cycle. However, these disadvantages do not appear to apply to the JTEC device, as its operation does not rely on moving mechanical components (see [Sect. 5.5.1](#)).

Late in Ericsson's career, he patented an engine [34] that operated using the Stirling cycle. The engine used an arrangement now commonly known as the Gamma Stirling engine type (see [Sect. 2.1.2](#)).

2.4.3 MEMS Ericsson Engines

The JTEC device is the only known example of an Ericsson cycle device that has been proposed at MEMS scale. See [Sect. 5.5.1](#) for further details.

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